# Isolation of Flow and Nonflow by Two- and Multi-Particle Cumulant Measurements of $v_n$ in $\sqrt{s_{NN}}$ = 200 GeV Au+Au Collisions by STAR

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**Abstract**

We apply a data-driven method to STAR Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV to isolate $\Delta\eta$-dependent and $\Delta\eta$-independent correlations by using two- and four-particle Q-cumulant $v_n$ measurements. The $\Delta\eta$-independent part, dominated by flow, is found to be $\eta$-independent within the STAR TPC of ±1 unit of pseudo-rapidity. The $\Delta\eta$-dependent part may be associated to nonflow, and is responsible for the $\Delta\eta$ drop in the measured two-particle $v_2$ cumulant. We combine our result to four- and six-particle cumulants to gain further insights on the nature of flow fluctuations.

## 1. Introduction

Heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) provide a means to study the Quark Gluon Plasma (QGP). In a non-central collision, the transverse overlap region is anisotropic. The energy density gradient converts the initial coordinate-space anisotropy into the final momentum-space one, generally called flow. As the system expands, the coordinate-space anisotropy diminishes. Hence, flow is sensitive mostly to the early stage of the collision [1]. Through measurements of anisotropic flow and comparison to hydrodynamic calculations, properties of the early stage of the collision system may be extracted. For example, the shear viscosity to entropy density ratio ($\eta/s$) of the QGP was found to be not much larger than the conjectured quantum limit of $1/4\pi$ [2].

The momentum-space anisotropic flow can be characterized by the Fourier coefficients of the particle azimuthal distribution relative to a symmetry plane (participant plane) [3]. However, the participant plane is not experimentally accessible. As a proxy, the event plane is constructed from particle momentum. Similarly, two- and multi-particle correlations are also used to quantify anisotropy. These various flow measurements are therefore contaminated by intrinsic particle correlations unrelated to the participant plane, generally called nonflow [4]. Although nonflow at low transverse momentum ($p_T$) may be small, it was found that $\eta/s$ is very sensitive to flow [5]. Therefore, it is important to separate the nonflow contributions from flow measurements.

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[1]A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

## 2. Measurement Methods

This analysis attempts to separate flow and nonflow in a data-driven manner [6]. The method utilizes two-particle cumulant with one particle at $\eta_\alpha$ and another at $\eta_\beta$, and four-particle cumulant with two at $\eta_\alpha$ and two at $\eta_\beta$. We have

$$V\{2\} \equiv \langle\langle 2\rangle\rangle \equiv v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta\eta) + \delta(\Delta\eta), \tag{1}$$

$$V\{4\} \equiv \sqrt{2\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle} \approx v(\eta_\alpha)v(\eta_\beta) - \sigma(\eta_\alpha)\sigma(\eta_\beta) - \sigma'(\Delta\eta), \tag{2}$$

where $\Delta\eta = \eta_\beta - \eta_\alpha$, and we require $\eta_\alpha < \eta_\beta < 0$. The average flow ($v$) is only a function of $\eta$. $\sigma$ and $\sigma'$ are the flow fluctuation, which may have $\Delta\eta$-dependence component. Nonflow ($\delta$) is generally a function of $\Delta\eta$.

We take the difference between cumulants $V_n\{2\}$ at $(\eta_\alpha, \eta_\beta)$ and $(\eta_\alpha, -\eta_\beta)$. We do the same for $V_n\{4\}$. For symmetric collision systems, the $\Delta\eta$-independent terms in Eq. (1) and (2) cancel out, leading to Eq. (3) and (4):

$$\Delta V\{2\} \equiv V\{2\}(\eta_\alpha, \eta_\beta) - V\{2\}(\eta_\alpha, -\eta_\beta) \equiv V\{2\}(\Delta\eta_1) - V\{2\}(\Delta\eta_2) = \Delta\sigma' + \Delta\delta, \tag{3}$$

$$\Delta V\{4\} \equiv V\{4\}(\eta_\alpha, \eta_\beta) - V\{4\}(\eta_\alpha, -\eta_\beta) \equiv V\{4\}(\Delta\eta_1) - V\{4\}(\Delta\eta_2) \approx -\Delta\sigma', \tag{4}$$

where $\Delta\sigma' = \sigma'(\Delta\eta_1) - \sigma'(\Delta\eta_2)$, $\Delta\delta = \delta(\Delta\eta_1) - \delta(\Delta\eta_2)$, and $\Delta\eta_1 \equiv \eta_\beta - \eta_\alpha$, $\Delta\eta_2 \equiv -\eta_\beta - \eta_\alpha$. Assuming the same flow fluctuations $\sigma'$ in both $V\{2\}$ and $V\{4\}$, we can extract information of nonflow ($\delta$) and $\Delta\eta$-dependent flow fluctuation ($\sigma'$). Using Eq. (1) and (2), we can further obtain $v$ and $\sigma$.

## 3. Data Analysis and Results

We analyze the data in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from year 2004 measured by the STAR Time Projection Chamber (TPC) within $|\eta| < 1.0$. The Q-cumulant method [7, 8] is used with the acceptance correction in calculation. Azimuthal moments are weighted by unit (not pair/quadrant multiplicities).

Figure 1 (a), (b) and (c) show the cumulant results in Eq. (1) and (2) as a function of $\eta_\alpha$, $\eta_\beta$, and (d), (e) and (f) show the quantities in Eq. (3) and (4) for 20-30% centrality. $\Delta V_2\{4\}$ is shown in Fig. 1 (d), and is consistent with zero, suggesting that elliptic flow fluctuations are independent of $\Delta\eta$ within the TPC acceptance. This is used in subsequent analysis of data. We further assume the triangular flow fluctuations are also independent of $\Delta\eta$ within the TPC acceptance. With this taken into account, $\Delta V\{2\}$ will only have nonflow component. $\Delta V_2\{2\}$ and $\Delta V_3\{2\}$ is shown in Fig. 1 (e) and (f), respectively.

As the dashed lines shown in Fig. 1 (e) and (f), the nonflow difference between $\Delta\eta_1$ and $\Delta\eta_2$ appears linear in $\Delta\eta_2 - \Delta\eta_1$, with a slope that is independent of $\Delta\eta_1$. The intercept of the linear dependence decreases quickly with $\Delta\eta_1$, suggesting a short-range exponential component in nonflow. In other words, the nonflow difference can be described by

$$\delta(\Delta\eta_1) - \delta(\Delta\eta_2) = a[e^{\frac{-\Delta\eta_1}{b}} - e^{\frac{-\Delta\eta_2}{b}}] + A[e^{\frac{-\Delta\eta_1^2}{2\sigma^2}} - e^{\frac{-\Delta\eta_2^2}{2\sigma^2}}]. \tag{5}$$

A single fit of Eq. (5) with four free parameters $a, b, A, \sigma$ is applied to all the data points, yielding the solid curves in Fig. 1 (e) and (f). The fit results give the following nonflow parameterization:

$$\delta(\Delta\eta) = ae^{\frac{-\Delta\eta}{b}} + Ae^{\frac{-\Delta\eta^2}{2\sigma^2}}. \tag{6}$$
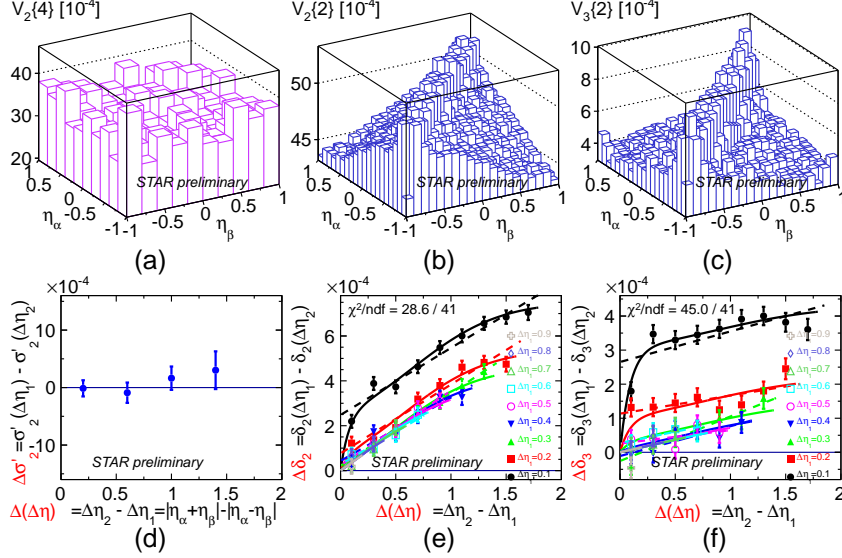
Figure 1: (a) The second harmonic four-particle cumulant. (b,c) The second and third harmonic two-particle cumulants. (d) Difference in $V_2\{4\}$ between $(\eta_\alpha, \eta_\beta)$ and $(\eta_\alpha, -\eta_\beta)$ as a function of $\Delta\eta_2 - \Delta\eta_1 = |2\eta_\beta|$. (e,f) Difference in $V_2\{2\}$ and $V_3\{2\}$ for given $\Delta\eta_1$ values, respectively. Data are from the 20-30% centrality of Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV.

Subtracting Eq. (6) from the raw two-particle cumulant gives the decomposed 'flow' results in Fig. 2 (a) and (b). Here the decomposed flow includes the flow fluctuation effect $\langle v(\eta_\alpha)v(\eta_\beta)\rangle = v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta)$.

Figure 2 (a) and (b) shows that $vv + \sigma\sigma$ is independent of $\eta$ for both $v_2$ and $v_3$, and Fig. 1 (a) shows $v_2 v_2 - \sigma_2 \sigma_2$ is independent of $\eta$. This suggests that $v_2$ and its fluctuation are independent of $\eta$. The projections of Fig. 2 (a), Fig. 1 (a) and (b) are shown in Fig. 2 (c). The difference between the raw two-particle cumulant $V_2\{2\}$ and the decomposed 'flow' $\langle v_2^2 \rangle$ is the nonflow effect. We find that $\delta_2/v_2^2$ is about 4%, and $\sigma_2^2/v_2^2$ is about 13% for the centrality 20-30%. Figure 3 shows the decomposed 'flow' and nonflow as a function of centrality in Au+Au $\sqrt{s_{NN}} = 200$ GeV.

The flow fluctuation may also be assessed by four- and six-particle cumulants. Assuming a Gaussian fluctuation of the flow magnitude, we have $v\{6\}/v\{4\} \approx 1 - \sigma^6/3v^6$, when $\sigma^2/v^2 \ll 1$ [8]. On the other hand, independent Gaussian fluctuations of $v_x, v_y$ would give $v\{6\} = v\{4\}$ [9]. We show in Fig. 4 $v_2\{6\}/v_2\{4\}$ vs the fluctuation results from our decomposition method. The systematic errors are estimated by the different moment weight methods and non-uniform acceptance correction. The $v_2$ results, while favoring Gaussian fluctuations in the flow magnitude, may be also consistent with Gaussian fluctuations in the individual flow components. A firmer conclusion on the nature of flow fluctuations await for more statistics.

## 4. Summary

We analyze two- and four-particle Q-cumulants between pseudo-rapidity bins in Au+Au collisions at 200 GeV from STAR. Exploiting the collision symmetry about mid-rapidity, we
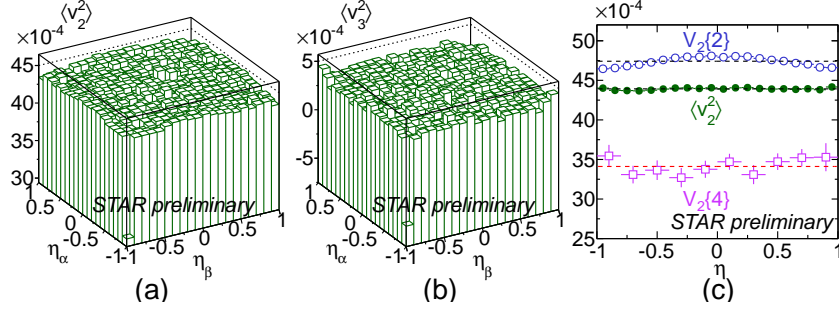
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Figure 2: (a) $\langle v_2^2 \rangle$. (b) $\langle v_3^2 \rangle$ as a function of $(\eta_\alpha, \eta_\beta)$. The parameterized nonflow has been subtracted. (c) the projection of $\eta$ dependence of the decomposed flow $\langle v_2^2 \rangle$ and the raw two- and four-particle cumulants of $v_2$ for the 20-30% centrality of Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV.
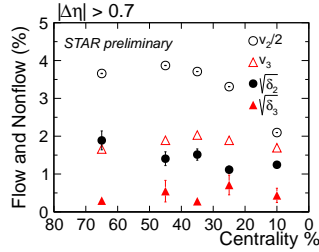


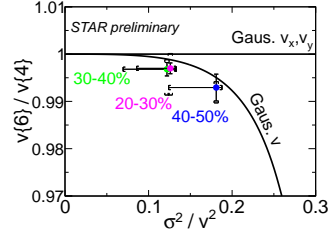Figure 3: the decomposed flow and nonflow with $\eta$-gap > 0.7 as a function of centralities

Figure 4: $v_2\{6\}/v_2\{4\}$ and $\sigma_2^2/v_2^2$. The curves are model predictions of ref. [9] and [8]

isolate the $\Delta\eta$-dependent and $\Delta\eta$-independent correlations in the data. Elliptic flow fluctuations appear independent of $\Delta\eta$ within the TPC acceptance, as deduced from the four-particle cumulant measurement. The method does not make assumptions about the $\eta$ dependence of flow. Our isolated $\Delta\eta$-independent part of our data is dominated by flow, with a relatively small away-side nonflow, and is found to be $\eta$-independent within the STAR TPC of $\pm 1$ unit of pseudo-rapidity. The $\Delta\eta$-dependent part is nonflow and is found to decrease with $\Delta\eta$. In the 20-30% Au+Au collisions at $|\eta| < 1$, and $p_T < 2$ GeV/$c$, the elliptic nonflow relative to flow $\delta_2/\langle v_2^2 \rangle$ is found to be 4% and the relative fluctuation $\sigma_2^2/\langle v_2^2 \rangle$ is 13%. The flow fluctuation in conjunction with the 6- and 4-particle cumulants flow ratio seems to favor Gaussian fluctuations in the flow magnitude.

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